(12) UK Patent Application (19) GB (11) 2 326 275 (13) A

(43) Date of A Publication 16.12.1998

(21) Application No 9712052.1

(22) Date of Filing 10.06.1997

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(51) INT CL^{6}
H01L 41/113 , H01J 7/00 , H02J 7/14

(52) UK CL (Edition P)
H1E EAGF E5 E8
H2H HBCH H23B
U1S S1820

(56) Documents Cited
US 4467236 A

(58) Field of Search
UK CL (Edition O) **H1E EAGF EAGG**
INT CL^{6} **H01L 41/113**
ONLINE: WPI, JAPIO, CLAIMS

(54) Abstract Title

Piezoelectric battery charger using wafer-array of piezoelectric elements attached to a source of mechanical vibrations, e.g. a motor vehicle engine

(57) The piezoelectric generator generates electricity by using the mechanical vibrational energy of an engine of a vehicle. The piezoelectric generator includes a wafer bearing an array of piezoelectric elements 205 attached to the engine and an electrical circuit for storing the electrical energy generated in the piezoelectric elements by charging a battery 150.

Each piezoelectric element has a cantilevered piezoelectric thin film 210 and a support member 220. Residual stresses are applied to the support member so that the piezoelectric elements are bent upward. The piezoelectric thin film is formed by using PZT, and the support member is formed by using SiNx.

When the engine vibrates, electrical energy is generated due to the stresses applied to the piezoelectric thin film, and the electrical energy is stored in the battery via a DC/AC converter. Thus electrical energy is effectively generated from wasted mechanical vibrational energy and is used in an electrical system.

Details of the manufacture of the piezoelectric elements are disclosed.

FIG. 4

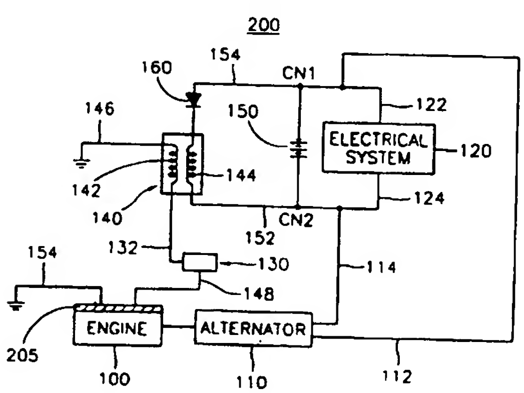

FIG. 5

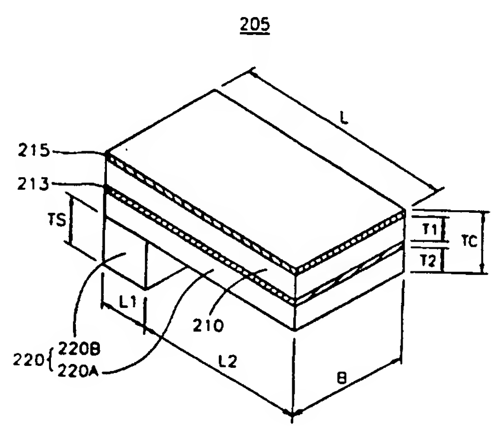

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FIG. 1
(PRIOR ART)

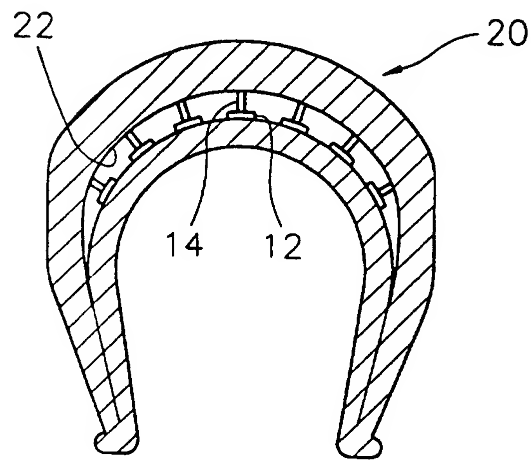


FIG. 2
(PRIOR ART)

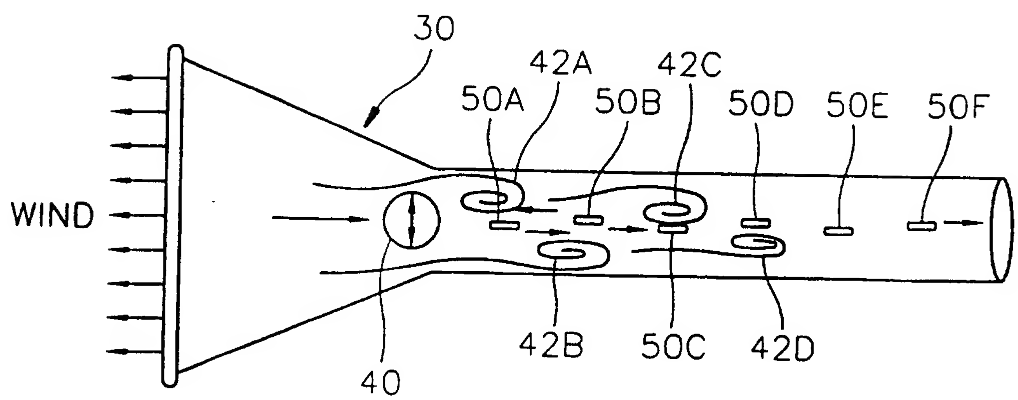


FIG. 3

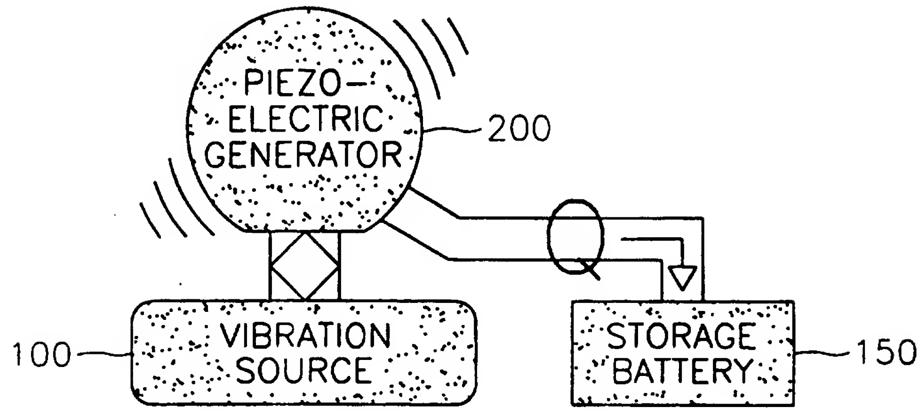

PIEZO-
ELECTRIC
GENERATOR
200
100
VIBRATION
SOURCE
STORAGE
BATTERY
150

FIG. 4

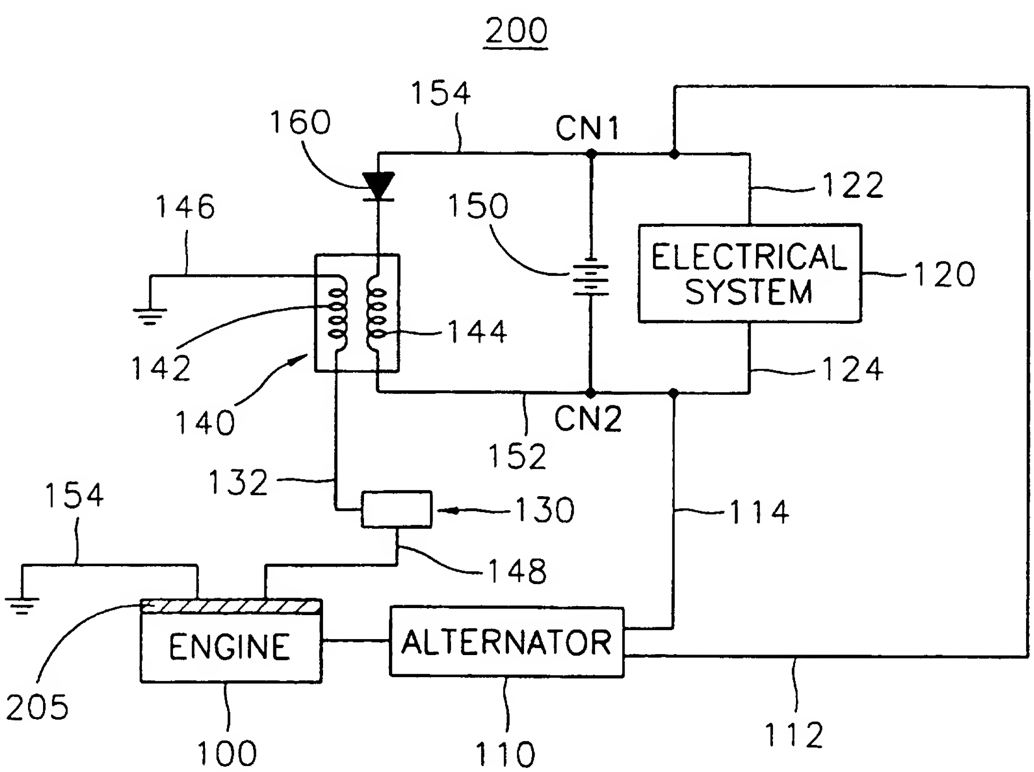

200
154
160
CN1
146
150
122
ELECTRICAL
SYSTEM
120
144
142
124
140
CN2
152
154
132
130
114
148
205
ENGINE
ALTERNATOR
100
110
112

FIG. 5

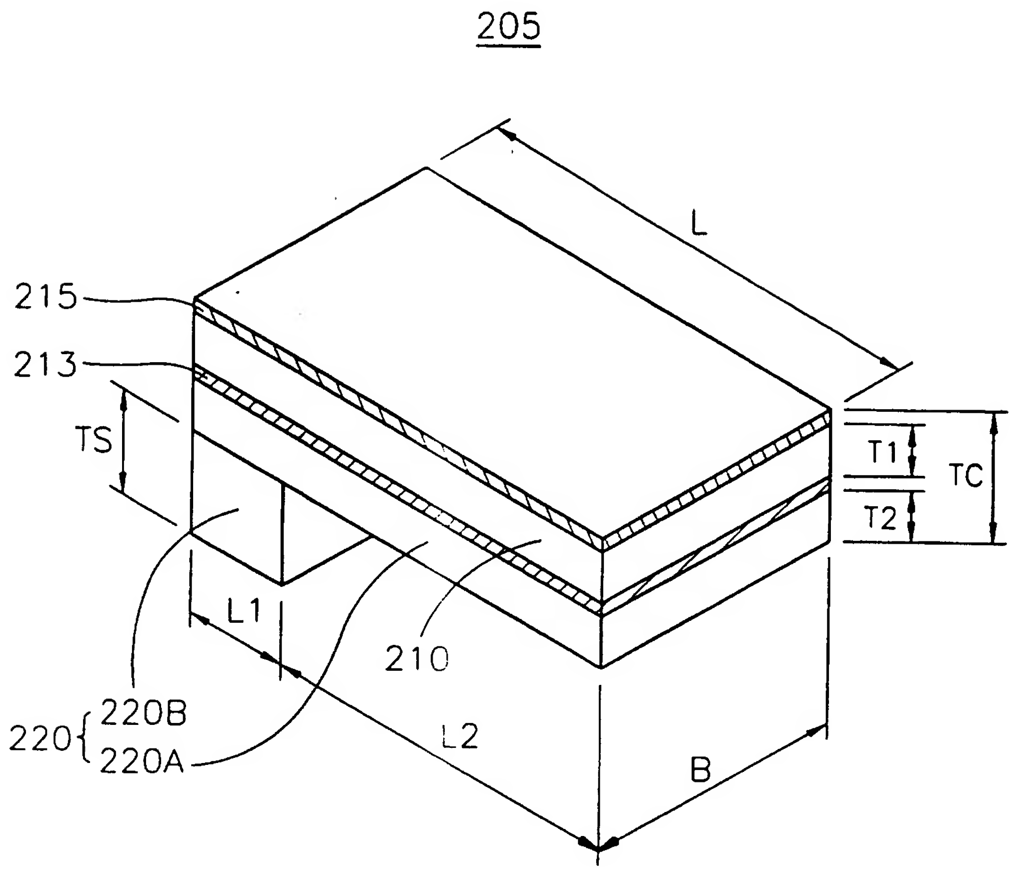


FIG. 6

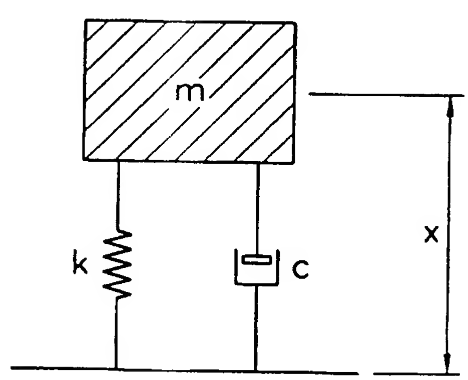


FIG. 7A

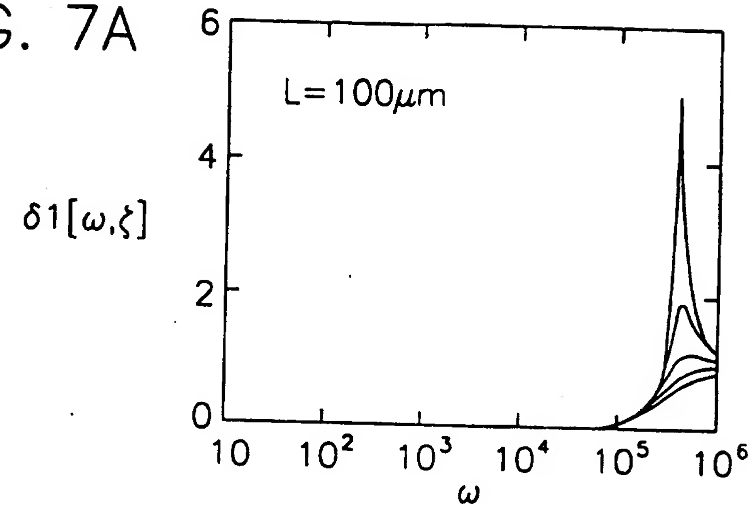


FIG. 7B

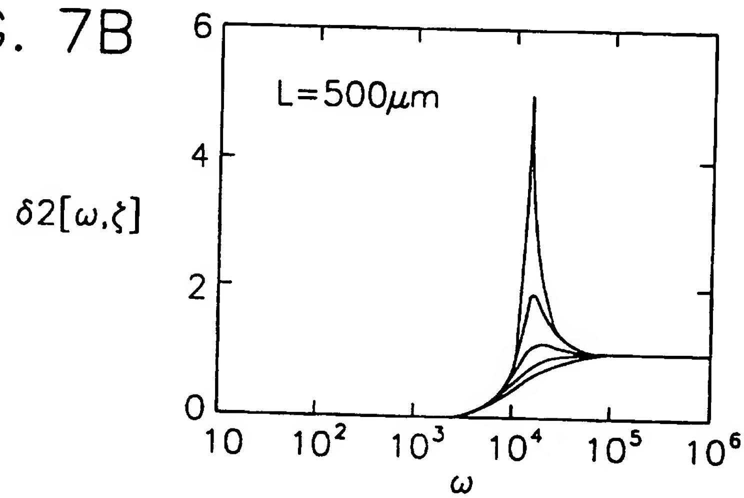


FIG. 7C

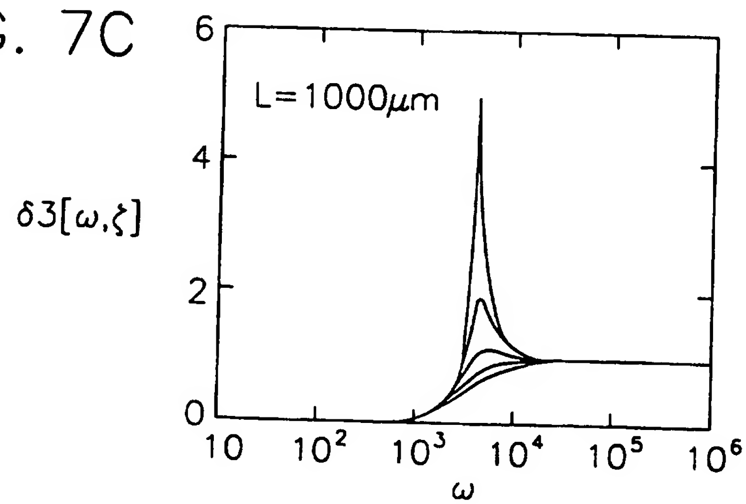
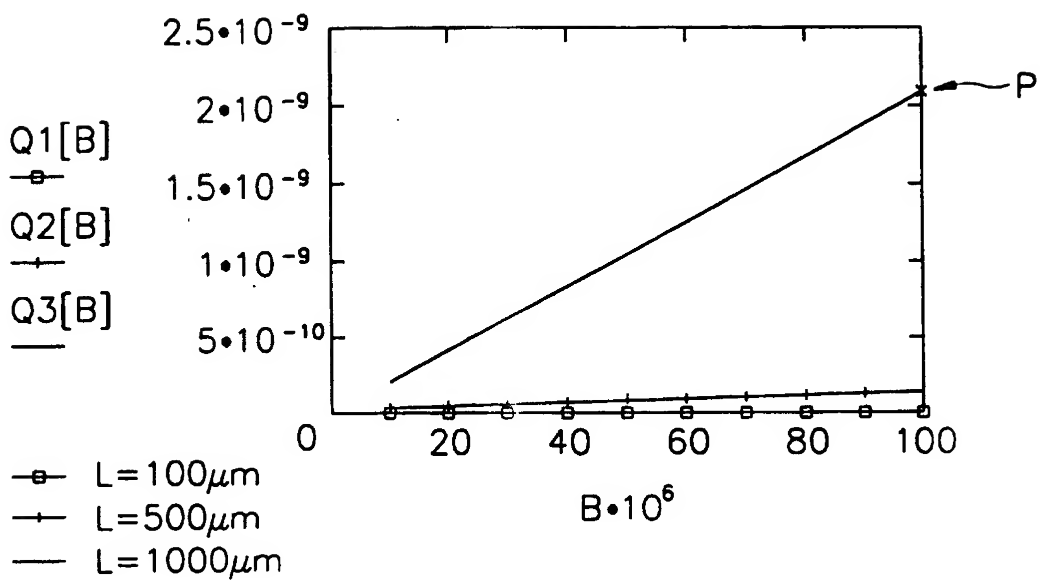
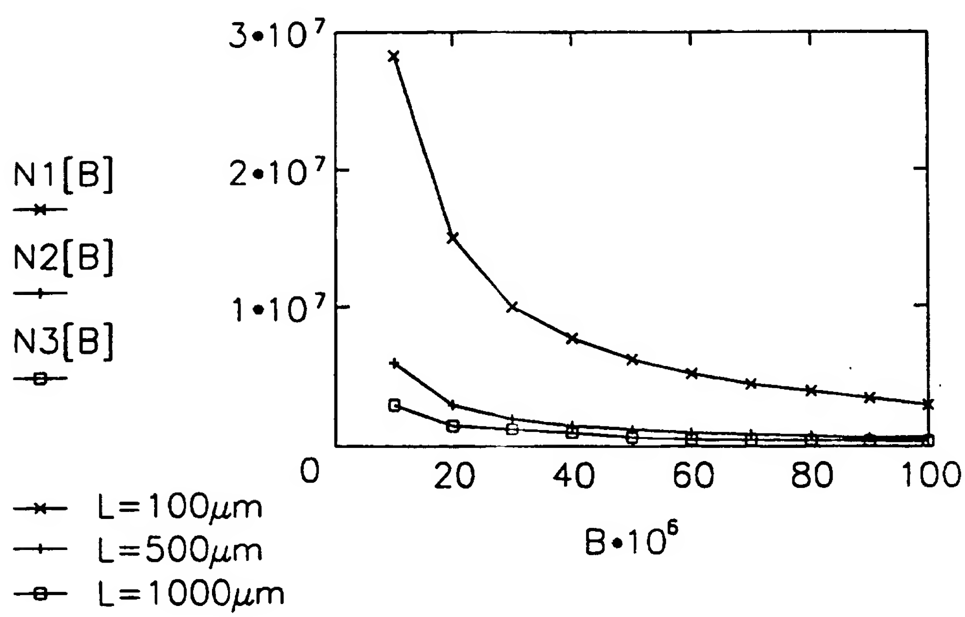


FIG. 8



2.5•10^-9
2•10^-9
1.5•10^-9
1•10^-9
5•10^-10
0
20
40
60
80
100
P
Q1[B]
Q2[B]
Q3[B]
B•10^6
L=100μm
L=500μm
L=1000μm

FIG. 9



3•10^7
2•10^7
1•10^7
0
20
40
60
80
100
N1[B]
N2[B]
N3[B]
B•10^6
L=100μm
L=500μm
L=1000μm

FIG. 10

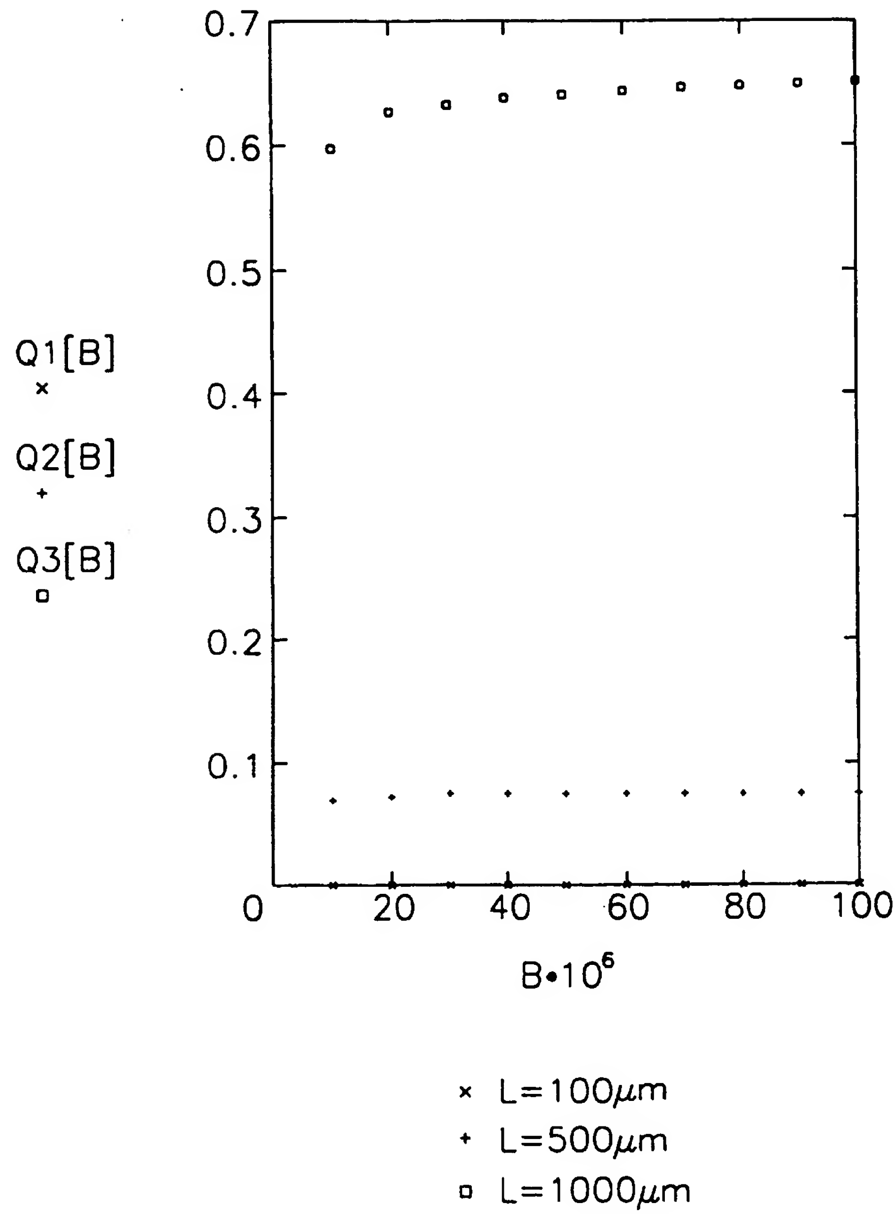

0.7
0.6
0.5
0.4
0.3
0.2
0.1
Q1[B]
×
Q2[B]
+
Q3[B]
□
0
20
40
60
80
100
B•10^6
× L=100μm
+ L=500μm
□ L=1000μm

FIG. 11A

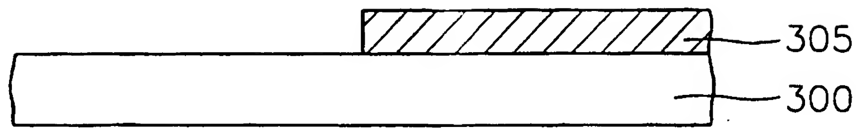


FIG. 11B

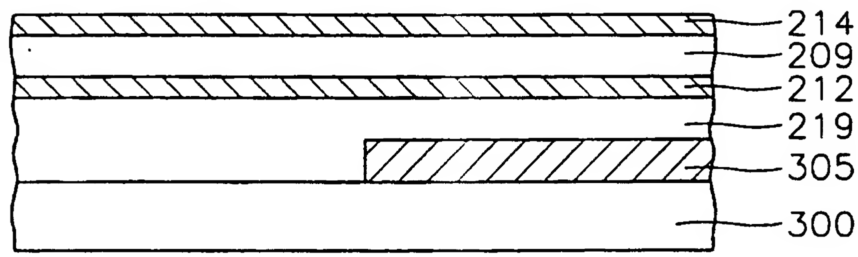


FIG. 11C

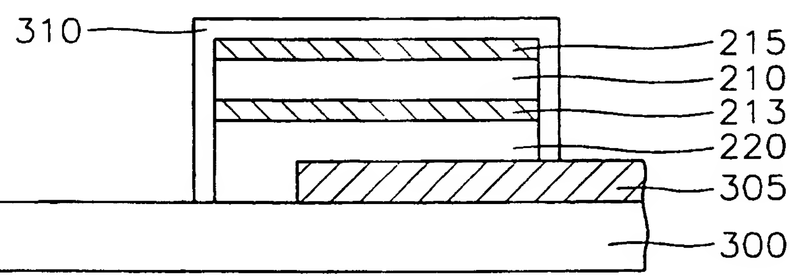
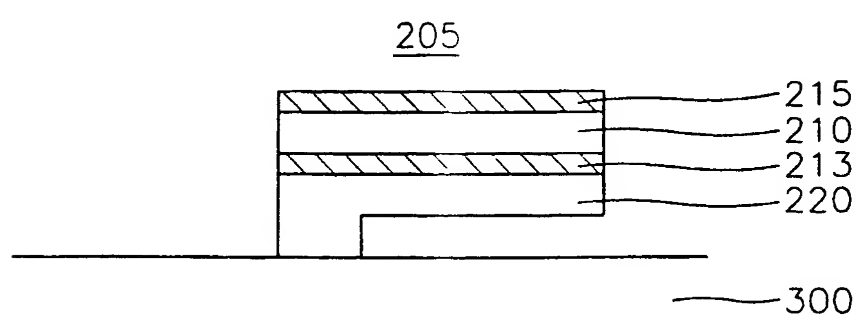


FIG. 11D



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PIEZOELECTRIC GENERATOR FOR GENERATING ELECTRICITY USING PIEZOELECTRIC ELEMENTS ATTACHED TO A VIBRATION SOURCE AND METHOD FOR MANUFACTURING THE SAME

The present invention relates to a piezoelectric generator and a method for manufacturing the piezoelectric generator, and more particularly to a piezoelectric generator which generates electricity by using piezoelectric elements attached to a mechanical vibration source and a method for manufacturing the piezoelectric generator.

Piezoelectricity exists in a group of special crystals, and is accompanied by a direct piezoelectric effect and an inverse piezoelectric effect. The direct piezoelectric effect is an effect where electric charges are generated in a piezoelectric material when forces or stresses are exerted onto the material, and the inverse piezoelectric effect is an effect where a piezoelectric material is deformed when current flows through the material. Therefore, conversion of mechanical energy into electrical energy or vice versa is possible by using the piezoelectricity. The direct piezoelectric effect is widely used in a sensor that detects mechanical changes in the form of current changes, and the inverse piezoelectric effect is mainly used as the principle of an actuator.

Since the piezoelectricity of piezoelectric materials was discovered, sensors which detect mechanical changes by using the direct piezoelectric effect has been developed, and an example of such a sensor is disclosed in U.S. Patent No. 4,924,131 issued to Nakayama Shiro et al. and entitled "Piezoelectric Acceleration Sensor". The sensor of Shiro includes piezoelectric polymer membrane elements and a diaphragm, and detects acceleration applied to the diaphragm by using currents generated by deformations of the piezoelectric elements. A plurality of other examples of such sensors which use piezoelectricity are disclosed in U.S. Patent No. 4,904,499 issued to Miura Shinsuke et

al. and entitled "Device for Detecting Viscosity or Specific Gravity of Liquid" and in U.S. Patent No. 5,083,466 issued to Holm-Kennedy James W. et al. and entitled "Multidimensional Force Sensor" and the like.

Meanwhile, examples of such sensors that detect knocking or vibrations by using piezoelectric elements are disclosed in U.S. Patent No. 4,672,839 issued to Takeuchi Tadashi et al. and entitled "Vibration Sensor", and in U.S. Patent No. 4,6660,410 issued to Entenmann Robert et al., assigned to Robert Bosch Gmbh and entitled "Knock Sensor" and the like.

Recently, several studies has been conducted about piezoelectric generators which generate useful electrical energy by using stresses applied to piezoelectric elements in order to use the direct piezoelectric effect positively. An example of such a piezoelectric generator is disclosed in U.S. Patent No. 5,341,062 issued to Cero Jr. Joseph T. et al. and entitled "Piezoelectric Energy Generator". U.S. Patent No. 4,504,761 issued to Charles G. Triplett and entitled "Vehicular Mounted Piezoelectric Generator" discloses a piezoelectric generator which is mounted to a tire of a vehicle and generates electricity by using stresses applied to the tire during rotation of a wheel of the vehicle. Further, U.S. Patent No. 5,223,763 issued to David B. Chang and entitled "Wind Power Generator and Velocimeter" discloses a piezoelectric generator which generates electricity in piezoelectric elements by vortices.

FIG. 1 schematically shows a tire to which the piezoelectric generator of Triplett is mounted. Referring to FIG. 1, the piezoelectric generator of Triplett includes a piezoelectric array having a multiplicity of piezoelectric elements 12 attached to the upper surface of an inner wall of the tire 20 and having stressing members 14 for stressing or distorting the piezoelectric elements 12. When the vehicle is propelled on a roadway, the

stressing members 14 makes contact with the corresponding piezoelectric elements 12 and applies stresses to the piezoelectric elements 12, thereby generating electricity in the piezoelectric elements 12. The piezoelectric elements 12 are electrically connected to a storage battery or an electrical system of the vehicle.

FIG. 2 shows the piezoelectric generator of Chang which generates electricity by using winds. Referring to FIG. 2, the piezoelectric generator of Chang includes a conduit 30 which guides wind flow and a baffle 40 which forms vortices in the flow. A plurality of piezoelectric elements 50A through 50F are positioned in sequence of a predetermined distance from each other in the path of the flow. When stresses are applied to the piezoelectric elements by the vortices, electricity is generated in the piezoelectric elements 50A through 50F.

However, in spite of their usefulness, there has not been many studies on piezoelectric generators which convert mechanical energy to useful electrical energy. Further, since machining of electrical elements is difficult and efficiencies of the piezoelectric generators are not so high, there exists a lot of problems to be solved in order to practically use the piezoelectric generators.

Therefore, it is an object of the present invention to provide a piezoelectric generator which generates electricity using vibrational energy of a mechanical vibration source.

It is another object of the present invention to provide a piezoelectric generator which effectively generates electricity.

It is another object of the present invention to provide a manufacturing method for manufacturing the above-mentioned piezoelectric generator.

In order to accomplish the above-mentioned objects of the present invention, the piezoelectric generator comprises a multiplicity of piezoelectric elements provided on a wafer attached to a mechanical vibration source, for generating electrical energy from vibrational energy of the mechanical vibration source, each piezoelectric element including a piezoelectric thin film and a support member formed on a lower side of the piezoelectric thin film, the support member having a deformable portion deformed together with the piezoelectric thin film by vibration of the mechanical vibration source and having a support portion integrally formed with one side of the deformable portion for supporting the piezoelectric thin film and the deformable portion; and an electric circuit for storing the electrical energy generated in the piezoelectric element in a storage battery.

According to one aspect of the present invention, the deformable portion and the support portion of the support member are substantially cube-shaped, respectively, and the lengths of the piezoelectric thin film and the deformable portion are sufficiently longer that the length of the support portion so that the piezoelectric element substantially acts as a piezoelectric cantilever. Residual stresses are applied to the piezoelectric elements, respectively, so that free ends of the piezoelectric elements are upwardly bent. The piezoelectric thin films are comprised of a material selected from the group consisting of ZnO, PZT, and PLZT, and the support members are comprised of a nitride. A first electrode is formed on the bottom portion of the piezoelectric thin film and a second electrode is formed on the top portion of the piezoelectric thin film so as to transfer the electrical energy generated in the piezoelectric element to the storage battery.
The first and second electrodes are comprised of a material selected from a group consisting of platinum, tantalum, or platinum-tantalum. The piezoelectric elements are

bonded to the wafer, and the piezoelectric elements are manufactured by surface micro-machining.

According to another aspect of the present invention, the electric circuit comprises a first lead wire electrically connected to the piezoelectric element, a second lead wire electrically connected to the piezoelectric element on one side thereof and grounded on the other side thereof, a high-voltage coil electrically connected to the first lead wire on one side thereof and grounded on the other side thereof, and a low-voltage coil electrically connected to positive and negative electrodes of the storage battery on one and the other sides thereof, respectively. A DC/AC converter provided in the first lead wire for converting direct current generated on the piezoelectric elements into indirect current is provided in the electric circuit. A diode provided between the storage battery and the transformer for preventing the storage battery from discharging electricity through the transformer is provided in the electric circuit.

The method for manufacturing a piezoelectric generator comprises the steps of forming a plurality of piezoelectric elements on a wafer attached to the vibration source for generating an electrical energy from a vibrational energy of a vibration source, the piezoelectric element forming step comprising i) forming a piezoelectric thin film, including forming a first electrode beneath the piezoelectric thin film and forming a second electrode on the piezoelectric thin film and ii) forming a support member having an actuating portion actuated by vibration of a vibration source and attached beneath the piezoelectric thin film having the first electrode and the second electrode, and having an support portion integrally formed with the actuating portion for supporting the actuating portion and the piezoelectric thin film; and forming an electrical circuit for storing the electrical energy generated from the piezoelectric elements into a storage battery.

According to the piezoelectric generator of the present invention, useful electrical energy is generated from the wasted mechanical vibrational energy. Further, it is possible to effectively generate electricity by selecting the shapes, the sizes, and the properties of the piezoelectric elements on a wafer such that the amount of electric charge generated in the piezoelectric element is maximized. In addition, the electrical energy generated in the piezoelectric elements is effectively stored in the storage battery by the electric circuit provided in the piezoelectric generator.

The above object and other advantages of the present invention will become more apparent by describing in detail preferred embodiments thereof with reference to the attached drawings in which:

FIG. 1 is a schematic view for illustrating a tire to which a piezoelectric generator is mounted;

FIG. 2 is a schematic view for illustrating a conventional piezoelectric generator which generates electricity by winds;

FIG. 3 is a schematic view for illustrating a basic concept of a piezoelectric generator according to the present invention;

FIG. 4 is a schematic view for illustrating a piezoelectric generator according to the present invention which is applied to an engine of a vehicle;

FIG. 5 is a perspective view for showing a piezoelectric element which is used in the piezoelectric generator of FIG. 4;

FIG. 6 is a schematic view for showing a simple mechanical model for analyzing the vibrational characteristics of the piezoelectric element of FIG. 5;

FIG. 7A through 7C are graphs for showing the natural frequency ω_n of a

piezoelectric cantilever element of FIG. 5;

FIG. 8 is a graph for showing an amount of electric charge generated in the piezoelectric element of FIG. 5;

FIG. 9 is a graph for illustrating the number N of the piezoelectric elements which can be machined on a Si-wafer;

FIG. 10 is a graph for showing the total amount of the electric charge generated in the piezoelectric elements formed on a wafer having a predetermined area; and

FIGs. 11A through 11D illustrate manufacturing steps of the piezoelectric element shown in FIG. 5.

Hereinafter, a piezoelectric generator and a method for manufacturing the piezoelectric generators according to a preferred embodiment of the present invention will be explained in more detail with reference to the accompanying drawings.

FIG. 3 is a schematic view for illustrating a basic concept of a piezoelectric generator according to the present invention. The piezoelectric generator 200 according to a preferred embodiment of the present invention is attached to a mechanical vibration source 100 of an engine of a vehicle or the like. When the vibration source 100 vibrates, piezoelectric elements of the piezoelectric generator 200 are deformed and electrical energy is generated in the piezoelectric elements. The piezoelectric generator 200 is electrically connected to a storage battery, and the electrical energy generated in the piezoelectric elements is stored in the storage battery.

FIG. 4 is a schematic view for illustrating a piezoelectric generator according to the present invention which is applied to an engine of a vehicle. Referring to FIG. 4, the piezoelectric generator 200 according to the present invention includes a multiplicity of

piezoelectric elements 205, and an electric circuit for storing electrical energy generated in the piezoelectric elements 205 in a storage battery 150. The multiplicity of piezoelectric elements 205 are provided on a wafer which is attached to an upper portion of an engine 100. The engine 100 is connected, by a belt drive mechanism, to a conventional alternator 110. During operation of the alternator 110, the alternator 110 reduces a running output of the vehicle, so when an electrical system does not need electricity or the battery is fully charged, the alternator 110 is not driven by the engine 100 but just idles. In contrast, since the piezoelectric generator 200 uses mechanical energy which is wasted by vibration of the engine 100 and does not reduce the running output of the vehicle during its operation, the piezoelectric generator 200 is operated prior to or together with the alternator 110.

As shown in FIG. 4, the electric circuit 105 includes a DC/AC converter 130, a transformer 140, and a diode 150. The piezoelectric elements 205 are electrically connected to first and second lead wires 148 and 154. The first and second lead wires 148 and 154 are in turn electrically connected to the ground and the DC/AC transformer 130 respectively. Direct current generated by the piezoelectric generator 200 is applied to the DC/AC converter 130 and is converted into indirect current. The DC/AC converter 130 is, through a third lead wire 132, electrically connected to a high-voltage coil 142 of the transformer 140. The high-voltage coil 142 is grounded through a fourth lead wire 146, and the indirect current converted by the DC/AC converter 130 flows through the high-voltage coil 142. A low-voltage coil 144 of the transformer 140 is electrically connected to positive and negative electrodes of the storage battery 150 through fifth and sixth lead wires 152 and 154.

The diode 160 is provided in the sixth lead wire 154, and positive and negative

electrodes of the diode 160 are electrically connected to the negative electrode of the storage battery 150 and the low-voltage coil 144 respectively. The diode 160 prevents the electrical energy from discharging through the transformer 140 from the storage battery 150.

The fifth lead wire 12 of the low-voltage coil 144 and the positive electrode of the storage battery 150 define a first connection node CN1, and the positive electrode of the diode 160 and the negative electrode of the storage battery 150 define a second connection node CN2. First and second output lead wires 112 and 114 of the alternator 110 are electrically connected to the first and second connection nodes CN1 and CN2. Power supply leads of the electrical system 120 are electrically connected to the first and second connection nodes CN1 and CN2 in order to supply electrical power to the electrical system 120.

FIG. 5 schematically shows a piezoelectric element which is used in the piezoelectric generator according to the present invention. As shown in FIG. 5, the piezoelectric element 205 includes a piezoelectric thin film 210, a first electrode 213 which is formed on the bottom portion of the piezoelectric thin film 210, a second electrode 215 which corresponds to the first electrode 213 and is formed on the top portion 210 of the piezoelectric thin film 210, and a support member 220 which is formed on the bottom portion of the first electrode 213 and supports the piezoelectric thin film 210. The piezoelectric thin film 210 is substantially cube-shaped and has a length L, a thickness T1, and a width B. The piezoelectric thin film 220 is formed by using a piezoelectric material such as ZnO, PZT ($Pb(Zr, Ti)O_3$) or PLZT ($(Pb, La)(Zr, Ti)O_3$). Preferably, the piezoelectric thin film 220 is formed by using PZT. PZT is a complete solid solution of lead zirconate ($PbZrO_3$) and lead titanate ($PbTiO_3$). PZT having a cubic

structure exists in a paraelectric phase at a high temperature. Orthorhombic structure PZT exists in an antiferroelectric phase, rhombohedral structure PZT exists in a ferroelectric phase, and tetragonal structure PZT exists in a ferromagnetic phase according to the composition ratio of Zr and Ti at a room temperature.

The first and second electrode layers 213 and 215 is formed by using an electrically conductive metal such as platinum (Pt), tantalum (Ta), or platinum-tantalum (Pt-Ta) . The first and second electrodes 213 and 215 transfer the electrical charges generated in the piezoelectric thin film 210.

The piezoelectric thin film 210 on which the first and second electrodes are formed is supported by the support member 220. The support member 220 is formed by using a nitride. The support member 220 has a substantially L-shaped cross section, and includes a deformable portion 220A which is detached to the piezoelectric thin film 210 and deformed together with the piezoelectric thin film 210 by the vibration of the engine 100, and a support portion 220B which is integrally formed with the deformable portion 220A on one side of the deformable portion 220A and supports the deformable portion 220A attached to the piezoelectric thin film 210. The deformable portion 220A is substantially cube-shaped and has a length L, a thickness T2, and a width B, and the support portion 220B is substantially cube-shaped and has a length L2, a thichness T2, and a width B. As shown in FIG. 5, the length L1 of the deformable portion 220A is sufficiently longer than the length L2 of the support portion 220B so that the piezoelectric element 205 acts as a piezoelectric cantilever of a length L1, a thickness Tc, and a width b.

Recently, M. Sakata et al. of OMRON Co. suggest an equation for measuring the piezoelectric coefficient of a piezoelectric element 205 which has a shape of FIG. 5, as

follows:

$$d_{31}=\frac{4L1^3Q}{3BTcE\delta L^2}\text{-----}(1)$$

where

d_{31} represents the piezoelectric coefficient of the piezoelectric element,

L1 represents the length of the piezoelectric cantilever element,

Q represents an amount of electric charge generated in the piezoelectric element,

B represents the width of the piezoelectric cantilever element,

Tc represents the thickness of the piezoelectric cantilever element,

δ represents the deformation of the piezoelectric thin film, and

L represents the total length of the piezoelectric element.

In the equation (1), the amount of electric charge Q is the amount of electric charge which is detected by the charge amplifier when the piezoelectric coefficient d_{31} of the piezoelectric element 205 is measured.

When the equation (1) is arranged in the form of the amount of electric charge Q, the result is as follows:

$$Q=\frac{3BTcE\delta L^2d_{31}}{4L1^3}\text{-----}(2)$$

As will be known in the equation (2), since the amount of electric charge Q is proportional to the piezoelectric coefficient d_{31}, it is preferable that the piezoelectric coefficient d_{31} be as large as possible in order to maximize the amount of electric charge Q. In the piezoelectric generator according to the preferred embodiment of the present invention, the piezoelectric thin film 210 is made of a piezoelectric material which has a relatively large coefficient between 80pC/N and 220pC/N.

Since the length L2 of the support portion 220B of the support member 220 is sufficiently shorter than the total length L of the piezoelectric element 205, the length L1 can be assumed to be equal to the length L for simplicity of analysis. Further, the piezoelectric coefficient d_{31} is assumed to be 100pC/N for convenience of calculation.

In the equation (1), the thickness T1 of the piezoelectric thin film 210 is assumed to be sufficiently smaller than the thickness T2 of the support member 220, and Young's modulus of the piezoelectric thin film 210 is ignored. However, in the vibrational analysis of the piezoelectric element 205 of the present invention, the thicknesses of the first and second electrodes 213 and 215 which are respectively formed on the top and bottom portion of the piezoelectric thin film 210 is ignored, but the thickness T1 of the piezoelectric thin film 210 is not ignored, and an equivalent Young's modulus of bi-layers is used in the equation.

The equivalent Young's modulus of bi-layers is as follows:

$$E_{eq} = \frac{E1n^3 + E2}{n^3 + 3n^2 + 3n + 1}, \quad n = \frac{T1}{T2} \text{-----(3)}$$

where

E1 represents the Young's modulus of the piezoelectric thin film 210, and

E2 represents the Young's modulus of the support member 220.

FIG. 6 shows a simple mechanical model for analyzing the vibrational characteristics of the piezoelectric element of the present invention. Referring to FIG. 6, the mechanical model of the piezoelectric cantilever element 205 includes a mass body of a mass m, a spring of a spring coefficient k, and a damper of a damping coefficient c. The spring and the damper are connected to the mass body in parallel.

The equation of motion for the mass body when an external force $F = A\sin(\omega t)$ by

the mechanical vibration source of the mechanical model is applied to the mass body, is as follows:

$$m\frac{d^2x}{dt^2}+c\,\frac{dx}{dt}+kx=mA\omega^2(\sin\ (\omega t))\text{-----}(4)$$

where

x represents a displacement of the mass body,

A represents an amplitude of the vibration source,

ω represent the frequency of the vibration source, and

t represent the time lapsed.

The solution of the equation (4) is as follows:

$$x(\gamma)=\delta=\frac{A\gamma^2}{\sqrt{(1-\gamma^2)+(2\zeta\gamma)^2}}\text{-----}(5)$$

where

ζ represents the damping ratio of the piezoelectric element 205, and

γ represents the ratio of the frequency ω of the vibration source to the natural frequency ω_n of the mechanical model.

The natural frequency ω_n of the mechanical model is as follows:

$$\omega_n^2=\frac{K_{eq}}{M_{eq}}\text{-----}(6)$$

where

K_{eq} represents the equivalent spring coefficient of the mechanical model, and

M_{eq} represents the equivalent mass of the mechanical model.

The properties, such as the Young's moduli and the densities, of PZT and SiNx

which are the materials of the piezoelectric cantilever, are used by the data which are known in the art, and the thicknesses of the piezoelectric thin film 210 and the deformable portion 220A are set as 1μm respectively. Table 1 represents the data used for the analysis of the amount of electric charge generated by the present invention.

Table 1

properties	Young's modulus	density	thickness
unit	N/m^2	Kg/m^3	μm
PZT	75×10^9	7900	1
SiNx	375×10^9	3100	1

Table 2 represents the kinds of variables and the ranges of the variables which are employed in order to preferably accomplish the present invention.

Table 2

variables	unit	minimum value	increased amount	maximum value
length	L(μm)	100	500	1000
width	B(μm)	10	10	100
frequency	ω(Hz)	100	500	500000

Table 3 represents the natural frequency ω_n of the piezoelectric cantilever element 205, which is obtained by calculation, and FIG. 7 graphically shows the natural frequency ω_n of the piezoelectric cantilever element 205.

Table 3

the length of cantilever, L(μm)	natural frequency, ω_n(kHz)
100	380
500	15.2
1000	3.80

As known in Table. 3, the natural frequency ω_n of the piezoelectric element 205 is inversely proportional to the square of the length L and is independent from the width B.

In the preferred embodiment of the present invention, the equation (2) is used in order to determine the size of the piezoelectric element 205 which maximizes the amount of the electric charge. Referring to the equation (2), it will be known that one of the most important variables for maximizing the amount of electric charge generated in each piezoelectric element 205 multiplied by the number of the piezoelectric elements 205 which can be machined on a circular wafer of a predetermined area is the length L of the piezoelectric element 205.

FIG. 8 shows the amount of electric charge generated in one piezoelectric element 205 with respect to the length L and the width B when the amplitude A of the vibration is 0.5mm. As shown in FIG. 8, the amount of the electric charge is linearly proportional to the width B of the piezoelectric element 205. Now referring to point P in FIG. 5, the amount of electric charge of about 2nC is generated during each vibrational cycle when the width B and the length L of the piezoelectric element 205 are 100μm and 1000μm respectively.

FIG. 9 illustrates the number N of the piezoelectric elements which can be machined on a Si-wafer with respect to the length L and the width B of the piezoelectric element 205, and FIG. 10 shows the amount of the electric charge Q (refer to FIG. 8) generated in one piezoelectric element multiplied by the number N (refer to FIG. 9) of the piezoelectric elements. Referring to FIG. 10, when the piezoelectric array consisting of the piezoelectric elements 205 which can be micro-machined on an 8-inch Si-wafer is oscillated to 1kHz, the maximum amount of electric charge generated is 0.648C per second, thereby generating a current of 648mA.

The most important variables for increasing the amount of electric charge Q generated in the piezoelectric generator 200 according to the present invention are the piezoelectric coefficient d_{31} of the piezoelectric thin film 210 and the Young's modulus of the support member 220. As will be known in equation (2), the amount of electric current Q is proportional to the piezoelectric coefficient d_{31} of the piezoelectric thin film 210 and inversely proportional to the Young's modulus of the support member 220. Now referring to Table 1, the Young's Modulus of SiNx forming the support member 200 is 375×10^9N/m, which is relatively small.

The deflection by the weight of the piezoelectric element 205 is 6.678μm, which is small enough to be ignored. Referring to Table 4, the deformation δ of the piezoelectric element 205 has a maximum value of 37μm (500μm$\times$0.074) when the amplitude of the vibration is 0.5mm and the length L of the piezoelectric element 205 is 1000μm. Since the deformation is much larger than the thickness of the sacrificial layer, the piezoelectric element 205 can collide with the substrate, thereby damaging the piezoelectric element 205. Therefore, even though the amount of electric charge can be increased by setting the thickness Tc of the piezoelectric element 205 as very thin, there is a limitation in reducing the thickness Tc of the piezoelectric element 205. The above-mentioned problem is reasonably settled by volume shrinkage during the PZT crystallization. The piezoelectric generator according to the preferred embodiment of the present invention effectively prevents the collision of the piezoelectric elements 205 with the substrate, while the thickness Tc of the piezoelectric elements 205 remains sufficiently thin by applying residual stresses to the support member 220 so that the piezoelectric elements 205 are bent upward.

The piezoelectric array of the present invention is manufactured by micro

machining. The piezoelectric array is manufactured by using Micro Electro Mechanical System (MEMS) where the piezoelectric thin film is bonded to the Si-wafer. Further, the piezoelectric array is manufactured by surface micro machining rather than bulk micro machining where cracks can be generated on the Si-wafer itself.

A method for manufacturing the piezoelectric element 205 according to the present embodiment will be described as follows.

FIGs. 11A through 11D illustrate manufacturing steps of the piezoelectric element 205 shown in FIG. 5. In FIGs. 11A through 11D, the same reference numerals are used for the same members in FIG. 5.

Referring to FIG. 11A, a sacrificial layer 305 is overlaid on a substrate 300 by a low pressure chemical vapor deposition (LPCVD) method. The sacrificial layer 305 is formed by using a phosphor-silicate glass (PSG) so that the sacrificial layer 305 has a thickness of between about 1.0μm and 5.0μm.

Subsequently, a portion of the sacrificial layer 305 is removed by etching considering a position on which the support portion 220B of the support member 220 is formed, so a portion of the substrate 300 is exposed.

Referring to FIG. 11B, a support layer 219 is formed on the exposed portion of the substrate 300 and on the sacrificial layer 305. The support layer 219 is formed by using a nitride and by a LPCVD method so that the support layer 219 has a thickness of between about 0.5μm and 2.0μm. Preferably, the support layer 219 has a thickness of about 1.0μm. The support layer 219 will be patterned so as to form the support member 220. A first electrode layer 212 is formed on the support layer 219. The first electrode layer 212 is formed by using an electrically conductive metal such as platinum (Pt), tantalum (Ta), or platinum-tantalum (Pt-Ta) and by a sputtering method or a chemical

vapor deposition (CVD) method so that the first electrode layer 212 has a thickness of between about 0.1μm and 1.0μm. Preferably, the first electrode layer 212 has a thickness of about 0.1μm. The first electrode layer 212 will be patterned so as to form the first electrode 213.

A piezoelectric layer 209 is overlaid on the first electrode layer 212 by a sol-gel method, a CVD method, or a sputtering method. The piezoelectric layer 209 is formed by using a piezoelectric material such as ZnO, PZT ($Pb(Zr, Ti)O_3$) or PLZT ($(Pb, La)(Zr, Ti)O_3$) so that the piezoelectric layer 209 has a thickness of between about 0.5μm and 2.0μm. Preferably, the piezoelectric layer 209 is formed by using PZT and by a sol-gel method so that the piezoelectric layer 209 has a thickness of about 1.0μm. After the piezoelectric layer 209 is annealed by a rapid thermal annealing (RTA) method, the piezoelectric layer 209 is polled. The piezoelectric layer 209 will be patterned so as to form the piezoelectric thin film 210.

A second electrode layer 214 is overlaid on the piezoelectric layer 209. The second electrode layer 214 is formed by using an electrically conductive metal such as platinum, tantalum, or platinum-tantalum and by a sputtering method or a CVD method so that the second electrode layer 214 has a thickness of between about 0.1μm and 1.0μm. The second electrode layer 214 will be patterned so as to form the second electrode 215.

Referring to FIG. 11C, after a first photo resist (not shown) is coated on the second electrode layer 214, the second electrode layer 214 is patterned so as to form the second electrode 215 by using the first photo resist as an etching mask. As a result, the second electrode 215 has a rectangular shape. Then, the first photo resist is removed by etching. The piezoelectric layer 209, the first electrode layer 212, and the support layer

219 are respectively patterned so as to form the piezoelectric thin film 210, the first electrode 213, and the support member 220 by using the same method as that of the second electrode 215. Hence, the piezoelectric thin film 210, the first electrode 213, and the support member 220 respectively have rectangular shapes.

Subsequently, a protection layer 310 is formed on the second electrode 215 and on lateral portions of the second electrode 215, the piezoelectric thin film 210, and the first electrode 213 by using a second photo resist and by a spin coating method. The protection layer 310 has a thickness of between about 1.5μm and 2.0μm. The protection layer 310 protects the piezoelectric thin film 210 having the first electrode 213 and the second electrode 215 while the sacrificial layer 305 is removed.

Referring to FIG. 11D, the sacrificial layer 305 are removed by using a vapor of hydrogen fluoride (HF) or a vapor of potassium hydroxide (KOH). The piezoelectric element 205 is completed after the protection layer 310 is removed by etching and the piezoelectric element 205 is separated from the substrate 300.

Hereinafter, the operation of the piezoelectric element according to the present invention will be described.

During the operation of the engine, pistons which reciprocate in cylinders generate vibration. When the engine 100 vibrates, periodic external forces are applied to the piezoelectric cantilever element 205 of the piezoelectric generator 200 attached to the upper portion of the engine 100, thereby deforming the piezoelectric elements 205. The deformations of the piezoelectric elements 205 generate electricity due to the above-mentioned direct piezoelectric effect.

The piezoelectric generator according to the preferred embodiment of the present invention effectively prevents the collision of the piezoelectric elements 205 with the

substrate, while the thickness Tc of the piezoelectric elements 205 remains sufficiently thin by applying residual stresses to the support member 220 so that the piezoelectric elements 205 are bent upward. The sizes of piezoelectric elements 205 are determined such that the amount of the electric charge generated in each piezoelectric element 205 multiplied by the number of the piezoelectric elements 205 which are machined on a wafer is maximized in order to effectively generate electricity.

The electrical energy generated in the piezoelectric elements 205 is stored in a storage battery 150 by the electric circuit 105. The direct current generated in the piezoelectric elements 205 is converted by the DC/AC converter into the indirect current. The indirect current flows through the high-voltage coil 142 of the transformer 140, and the low-voltage coil 144 of the transformer is electrically connected to the positive and negative electrodes of the storage battery 150. Then the electrical energy is stored in the storage battery 150. The diode 160 provided between the transformer 140 and the storage battery prevents the electrical energy form discharging from the storage battery 150 through the transformer 140. The storage battery 150 is electrically connected to the conventional alternator 110 of the vehicle and receives electrical energy from the alternator 110. During operation of the alternator 110, the alternator 110 reduces a running output of the vehicle, so when an electrical system does not need electricity or the battery is fully charged, the alternator 110 is not driven by the engine 100, but just idles. In contrary, since the piezoelectric generator 200 uses mechanical energy which is wasted by vibration of the engine 100 and does not reduce the running output of the vehicle during its operation, the piezoelectric generator 200 is operated prior to or together with the alternator 110.

According to the piezoelectric generator of the present invention, useful electrical

energy is generated from the wasted mechanical vibrational energy. Further, it is possible to effectively generate electricity by selecting the shapes, the sizes, and the properties of the piezoelectric elements on a wafer such that the amount of electric charge generated in the piezoelectric element is maximized. In addition, the electrical energy generated in the piezoelectric elements is effectively stored in the storage battery by the electric circuit provided in the piezoelectric generator.

Although the preferred embodiment of the invention has been described, it is understood that the present invention should not be limited to this preferred embodiment, but various changes and modifications can be made by one skilled in the art within the scope of the invention as hereinafter claimed.

What is claimed is:

1. A piezoelectric generator for generating electrical energy by deformation of piezoelectric elements thereof, wherein the piezoelectric generator comprises:

a multiplicity of piezoelectric elements provided on a wafer attached to a mechanical vibration source, for generating electrical energy from vibrational energy of the mechanical vibration source, each piezoelectric element including a piezoelectric thin film and a support member formed on a lower side of the piezoelectric thin film, the support member having a deformable portion deformed together with the piezoelectric thin film by vibration of the mechanical vibration source and having a support portion integrally formed with one side of the deformable portion for supporting the piezoelectric thin film and the deformable portion; and

an electric circuit for storing the electrical energy generated in the piezoelectric element in a storage battery.

2. A piezoelectric generator according to claim 1, wherein a first electrode is formed on the bottom portion of the piezoelectric thin film and a second electrode is formed on the top portion of the piezoelectric thin film so as to transfer the electrical energy generated in the piezoelectric element to the storage battery

3. A piezoelectric generator according to claim 2, wherein the first and second electrodes are comprised of a material selected from the group consisting of a platinum, a tantalum, or a platinum-tantalum.

4. A piezoelectric generator according to claim 1, wherein the mechanical vibration source is an engine.

5. A piezoelectric generator according to claim 1, wherein the deformable portion and the support portion of the support member are substantially cube-shaped respectively and the lengths of the piezoelectric thin film and the deformable portion are sufficiently longer that the length of the support portion so that the piezoelectric element substantially acts as a piezoelectric cantilever.

6. A piezoelectric generator according to claim 5, wherein residual stresses are applied to the piezoelectric elements, respectively, so that free ends of the piezoelectric elements are upwardly bent.

7. A piezoelectric generator according to claim 1, wherein the piezoelectric thin films are comprised of a material selected from the group consisting of ZnO, PZT, and PLZT.

8. A piezoelectric generator according to claim 1, wherein the support members are comprised of a nitride.

9. A piezoelectric generator according to claim 1, wherein the piezoelectric coefficient of the piezoelectric thin film is between 80pC/n and 220pC/N.

10. A piezoelectric generator according to claim 1, wherein the

Young's modulus of the support member is between 200×10^9N/m and 400×10^9N/m.

11. A piezoelectric generator according to claim 1, wherein the sizes of the piezoelectric elements are determined such that an amount of electric charge generated in one piezoelectric element multiplied by the number of the piezoelectric elements is maximized.

12. A piezoelectric generator according to claim 1, wherein the piezoelectric elements are bonded to the wafer.

13. A piezoelectric generator according to claim 1, wherein the piezoelectric elements are manufactured by surface micro-machining.

14. A piezoelectric generator according to claim 1, wherein the electric circuit comprises a first lead wire electrically connected to the piezoelectric element, a second lead wire electrically connected to the piezoelectric element on one side thereof and grounded on the other side thereof, a high-voltage coil electrically connected to the first lead wire on one side thereof and grounded on the other side thereof, and a low-voltage coil electrically connected to positive and negative electrodes of the storage battery on one and the other sides thereof, respectively.

15. A piezoelectric generator according to claim 14, wherein the electric circuit further comprises a DC/AC converter provided in the first lead wire for converting direct current generated on the piezoelectric elements into indirect current.

16. A piezoelectric generator according to claim 14, wherein the electric circuit further comprises a diode provided between the storage battery and the transformer for preventing the storage battery from discharging electricity through the transformer.

17. A method for manufacturing a piezoelectric generator, wherein the method comprises the steps of:

forming a plurality of piezoelectric elements on a wafer attached to the vibration source for generating an electrical energy from a vibrational energy of a vibration source, the piezoelectric element forming step comprising i) forming a piezoelectric thin film, including forming a first electrode beneath the piezoelectric thin film and forming a second electrode on the piezoelectric thin film and ii) forming a support member having an actuating portion actuated by vibration of a vibration source and attached beneath the piezoelectric thin film having the first electrode and the second electrode, and having an support portion integrally formed with the actuating portion for supporting the actuating portion and the piezoelectric thin film; and

forming an electrical circuit for storing the electrical energy generated from the piezoelectric elements into a storage battery.

18. The method for manufacturing a piezoelectric generator as claimed in claim 17, wherein the step of forming support member is performed after forming a sacrificial layer on a substrate by a low pressure chemical vapor deposition and removing a portion of the sacrificial layer by etching.

19. The method for manufacturing a piezoelectric generator as claimed in claim 18, wherein the step of forming the sacrificial layer is performed by using a phosphor-silicate glass so that the sacrificial layer has a thickness of between 1.0μm and 5.0μm.

20. The method for manufacturing a piezoelectric generator as claimed in claim 18, the step of forming the piezoelectric elements further comprising the steps of:

forming a protection layer on the second electrode and on lateral portions of the second electrode, the piezoelectric thin film, and the first electrode by using a photo resist; and

removing the sacrificial layer by using a hydrogen fluoride vapor.

21. The method for manufacturing a piezoelectric generator as claimed in claim 20, wherein the step of forming the protection layer is performed by a spin coating method.

22. The method for manufacturing a piezoelectric generator as claimed in claim 17, wherein the step of the support member is performed by using a nitride and by a low pressure chemical vapor deposition so that the support member has a thickness of between 0.5μm and 2.0μm.

23. The method for manufacturing a piezoelectric generator as claimed in claim 17, wherein the step of forming the first electrode is performed by a sputtering method.

24. The method for manufacturing a piezoelectric generator as claimed in claim 23, wherein the step of forming the first electrode is performed by using platinum, tantalum, or platinum-tantalum so that the first electrode has a thickness of between 0.1μm and 1.0μm.

25. The method for manufacturing a piezoelectric generator as claimed in claim 17, wherein the step of forming the piezoelectric thin film is performed by a sol-gel method, chemical vapor deposition method, or a sputtering method.

26. The method for manufacturing a piezoelectric generator as claimed in claim 25, wherein the step of forming the piezoelectric thin film is performed by ZnO, (Pb(Zr, Ti)O_3), or ((Pb, La)(Zr, Ti)O_3) so that the piezoelectric thin film has a thickness of between 0.5μm and 2.0μm.

27. The method for manufacturing a piezoelectric generator as claimed in claim 17, wherein the step of forming the second electrode is performed by a sputtering method.

28. The method for manufacturing a piezoelectric generator as claimed in claim 27, wherein the step of forming the second electrode is performed by using platinum, tantalum, or platinum-tantalum so that the second electrode has a thickness of between 0.1μm and 1.0μm.

29. A piezoelectric generator constructed and arranged substantially as herein described, with reference to and as illustrated in accompanying figures 3-11D.

30. A method for manufacturing a piezoelectric generator substantially as herein described, with reference to and as illustrated in accompanying figures 3-11D.

The Patent Office

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Application No:	GB 9712052.1	**Examiner:**	Peter Easterfield
Claims searched:	1 to 28	**Date of search:**	26 August 1997

Patents Act 1977
Search Report under Section 17

Databases searched:

UK Patent Office collections, including GB, EP, WO & US patent specifications, in:

UK Cl (Ed.O): H1E (EAGF, EAGG)

Int Cl (Ed.6): H01L 41/113

Other: Online: WPI, JAPIO, CLAIMS

Documents considered to be relevant:

Category	Identity of document and relevant passage	Relevant to claims
A	US 4467236 A (KOLM et al) see fig. 3	

X	Document indicating lack of novelty or inventive step	A	Document indicating technological background and/or state of the art.
Y	Document indicating lack of inventive step if combined with one or more other documents of same category.	P	Document published on or after the declared priority date but before the filing date of this invention.
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